Efficient Cumulus Parameterization for Long-Term Climate Studies: The GISS Scheme

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18.1 Introduction

The Goddard Institute for Space Studies general circulation model (GISS GCM) differs from most other general circulation models in that it is designed for use exclusively on global climate change problems. Typical applications include assessments of the climatic response to increasing greenhouse gas concentrations and volcanic eruptions, evaluations of unforced variability of the atmosphere-ocean system, paleoclimatic simulations, and process studies of other planetary atmospheres.

The decadal time scales and subtle variations of the hydrologic cycle characteristic of such integrations place special demands on the physical parameterizations used in the model. For moist convection, the requirements are as follows: 1) Faithful representation of moisture and heat transports, sources and sinks which determine water vapor, lapse rate, and cloud feedbacks in a changing climate. This necessitates a mass flux approach to parameterization, in which a calculated mass of subcloud air rises to its neutral buoyancy (detrainment) level and is compensated by downward-moving air that effects most of the heat and moisture transport. But in light of everything that has been learned about convection from field studies since the first mass flux schemes appeared in the late 1960's, it is imperative that we go beyond the traditional cumulus updraft-compensating subsidence rendering of cumulus dynamics. 2) Flexibility to respond to a changing climatic state. This argues against schemes that empirically adjust the vertical structure to specified current values of CAPE (convective available potential energy) or the cloud work function, as well as those that adjust the humidity to a fixed profile. 3) Computational efficiency to allow the model to be run on general purpose computers or workstations. This requires us to seek the simplest possible parameterization that can capture the essential physics of processes occurring in convective clusters. Given a physically viable framework, increasing detail can be incorporated as computational power inevitably increases, although such decisions necessarily involve trade-offs with the desire for increased fidelity in other physical parameterizations (e.g., boundary layer, ground hydrology, sea ice) and increased horizontal and vertical resolution.

18.2 The basic scheme: Model II

The operational version of the GISS GCM, known as model II (Hansen et al. 1983), utilizes a simple mass flux cumulus parameterization. Moist convection is diagnosed to occur whenever a parcel of air lifted adiabatically from some level l is buoyant with respect to the environment at the next highest level. In terms of the moist static energy h, the instability criterion can be written

$$h_c = h_l > h^*_{l+1}, \tag{18.2}$$

where the subscript c indicates the cloud parcel and the asterisk the saturation value for the environment. Virtual temperature corrections to the buoyancy are neglected. The parcel rises to the highest consecutive level at which the buoyancy criterion is satisfied. Convection can be initiated from all levels below the tropopause. A fixed 50% of the mass of the cloud-base layer rises in each event. There is no entrainment into the rising plume, and thus one cloud top per cloud base.

Latent heat release serves only to maintain plume buoyancy; heating / cooling of the environment occurs via compensating environmental subsidence, detrainment of cloud air at the cloud top, and reevaporation of falling precipitation. The tendency of dry static energy *s* due to a single convective event can thus be written (in σ coordinates)

$$\frac{\partial s}{\partial t} = -M_c \frac{\partial s}{\partial \sigma} + (s_c - s)\,\frac{M_c}{\Delta\sigma}\,\delta(\sigma - \sigma_T) - LE \qquad (18.2)$$

where M_c is the cumulus mass flux in units appropriate to σ coordinates, σ_T the cloud-top level. $\Delta\sigma$ the layer thickness, *L* the latent heat of evaporation / sublimation, and *E* the evaporation rate. An analogous equation applies for the moisture tendency. Water condensed in the updraft at each level is not transported upward, but precipitation is allowed to reevaporate as it falls. Evaporation is calculated by making 25% of the mass of each (generally unsaturated) layer above cloud base available to the falling precipitation. All condensate is allowed to evaporate until either there is none left or the specified layer fraction saturates. This ensures that convective rain will not saturate any full GCM layer. The condensate remaining after that fraction of each layer saturates determines the convective precipitation that falls to the next level. Below cloud base, a larger fraction (50%) of the layer is made available for evaporation to indirectly account for the fact that some rain falls through convective clouds and cannot evaporate above cloud base. Precipitating ice melts immediately upon crossing the 0° C level.

The convective plume and subsiding environment transport grid-scale horizontal momentum. Convective cloud cover is assigned as proportional to the mean pressure thickness of all model layers up to cloud top; the visible optical thickness τ = 8 per 100-mb depth of the cloud. All types of convection are predicted by the same criterion; differentiation between deep and shallow depends only on the cloud buoyancy.

18.3 Improvements for model III

a. *Mass flux closure*

The quasi-equilibrium concept of cumulus interactions with the large-scale environment is well supported by available observations (Arakawa and Chen 1987). For climate models, though, the most appealing strategy is to develop a closure that produces quasi-equilibrium as an output rather than specifying it as an input. This approach allows for the possibility of small yet potentially important climatic changes in CAPE or the cloud work function.

The fixed mass flux of model II does not produce quasi-equilibrium because it reacts only as an “on-off” switch to variations in the rate of destabilization by large-scale processes. For model III, currently under development, we have adopted a simple alternative. Since the scheme is triggered when a lifted parcel is buoyant with respect to the next highest layer, we transport enough mass to just neutralize the instability at cloud base, assuming an adjustment time equal to a physics time step (1 h); the required mass flux is obtained by iteration on an initial guess (Yao and DelGenio 1989). Reevaporation of falling precipitation is adjusted so that the available layer fraction above cloud base is half the fraction of the subcloud layer that rises in the updraft. Instability is judged by a modified version of requirement 1 that includes the effects of water vapor and condensate on buoyancy. Sensitivity tests show that doubling the adjustment time merely decreases the instantaneous mass flux while increasing the frequency of convective events, resulting in an almost identical monthly mean climate.

This closure constrains only the conditions at cloud base; the vertical structure is free to vary according to the model physics as represented by requirement 2. Thus, an appropriate test of the model is its ability to generate quasi-equilibrium variability. Arakawa and Chen (1987) have shown that in quasi-equilibrium, variations in the degree of conditional instability of the troposphere (diagnosed, for example, by the vertical gradient of h^*) should be negatively correlated with variations in near-surface relative humidity (indicated by the boundary layer value of $h - h^*$). Figure 18.1 demonstrates that the model III closure does in fact exhibit such behavior at both tropical land and ocean locations.

Analyses of satellite data from ISCCP (International Satellite Cloud Climatology Project) show that given the vertical resolution of current climate models, there are rarely more than two deep convective cloud-top levels present instantaneously within a GCM grid-box-sized area (DelGenio and Yao 1987). Thus, rather than admitting an entire spectrum of cumulus cloud tops at any moment, we allow for two cloud tops per cloud-base level in model III (Yao and Del Genio 1989). The plumes are differentiated by entrainment rate; one is undilute, mimicking a convective core, while the mass flux in the other grows fractionally with height at a rate of 0.2 km^{-1}. The nonentraining plume receives a fraction of the total cloud-base mass flux given by the large-scale convergence at cloud-base; this allows in effect for a lower overall entrainment rate in situations conducive to organized cluster formation as opposed to isolated airmass thunderstorms. The two-plume configuration has several advantages: 1) it yields the observed bimodal spectrum of cumulus cloud tops in the time mean and the possibility of simultaneous deep and shallow convection without invoking a separate shallow convection parameterization; 2) it allows for some of the convection within a grid box to reach the tropopause, as observed, while producing the midtroposphere maximum in cumulus heating characteristic of heavily convecting regions in the tropics.

b. Convective downdrafts

GMC with mass flux cumulus parameterizations commonly exhibit excessive cumulus heating and drying in the lower troposphere. This is a serious deficiency for models applied to climate problems, in which changes in low cloud cover and/or optical thickness can dominate cloud feedback. One possible reason for this problem is that the motions that compensate a cumulus updraft consist of more than just environmental subsidence. It is known, for example, that convective-scale downdrafts driven by precipitation loading and evaporation are a ubiquitous feature of precipitating convective systems. Downdraft air typically originates in the middle troposphere, with characteristics similar to those of air near the moist static energy minimum, and is carried to the surface. The downdraft is usually cool and dry and therefore fundamentally alters the convective stability of the planetary boundary layer (Barnes and Garstang 1982).

Downdrafts are the result of complex microphysics and mesoscale dynamics in convective clusters and are therefore difficult to represent both realistically and efficiently in GMC. For GISS model III we have implemented the first operational downdraft parameterization in any GCM (DelGenio and Yao 1988). For convective events penetrating more than two levels above cloud base, we simply test as the plume rises for the first level (if any) at which an evaporatively cooled equal mixture of cloud and environment air is negatively buoyant. Such mixing is expected at midlevels of convective systems, where cloud-scale and mesoscale low pressure cause dynamic entrainment of air with low moist static energy from outside the cloud. For typical environmental conditions, roughly equal mixtures of cloudy and clear air are most likely to be negatively buoyant. If such a level is found, a downdraft forms there with the properties of the mixture. Once formed, the downdraft penetrates to cloud base, evaporating precipitation formed at lower levels to the extent necessary to remain as close to saturation as possible. The downdraft mass flux is specified to be one-third of the updraft mass flux, based on estimates from field studies (Johnson 1976) and mesoscale models (Simpson et al. 1982). Environmental subsidence below the downdraft formation level is thus reduced by a factor of 1/3, while M_c is reduced above the downdraft formation level by the mass of cloud air mixed into the downdraft.

Figure 18.2 (upper) illustrates that the inclusion of downdrafts significantly cools the planetary boundary layer in the GISS GCM: one consequence of this is an increase in the mass flux associated with shallow convection. Furthermore, even though downdrafts dry the boundary layer, they are moist relative to the environmental subsidence they replace. As a result, low-level relative humidity in the tropics increases when downdraft effects are included in the GCM (Fig. 18.2, lower). This has important possible ramifications for climate sensitivity. Most GCMs exhibit a positive component of cloud feedback due to decreasing low cloud cover in a warming climate (DelGenio 1991). This effect is probably associated with increased cumulus subsidence drying. To the extent that downdrafts offset subsidence drying, they may act to produce a more neutral cloud cover component of cloud feedback. In sea surface temperature perturbation experiments with the GISS GCM, for example, model II cloud cover decreases by 1.3% in response to a 4°C warming, while a newer version of the GCM that includes downdrafts exhibits only a 0.4% decrease.

c. Mesoscale cirrus anvils

Cumulus clouds occupy a small fraction of the area of the tropics and therefore have a negligible radiative impact. Convection is often organized, however, into mesoscale clusters capped by upper-troposphere anvils with long life cycles that are evident in satellite images (Fu et al. 1990). The detrainment term in mass flux convection schemes injects saturated vapor into the environment at cloud top and thereby triggers cirrus cloud formation. The clouds are typically too thin, though, and their frequency underpredicted.

Part of the problem is that anvils are dynamic; mesoscale updrafts within anvil clouds enhance condensation and produce significant stratiform precipitation (cf. Houze and Betts 1981). In addition, some of the ice found in anvils is not formed locally but instead is detrained from accompanying cumulus updrafts, at all altitudes above the freezing level. GISS model III parameterizes these clouds with the aid of a prognostic cloud water budget for stratiform clouds (DelGenio and Yao 1990). In prognostic schemes, condensed water is carried as a predicted variable. Rather than forcing clouds to dissipate (evaporate or precipitate) in the same time step as they are formed, the scheme predicts the tendency of cloud water content due to microphysical sources (condensation) and sinks (autoconversion, accretion, evaporation). To simulate cumulus anvils, we add all convective condensate produced four model levels or more above cloud base (typically, from 550 mb to the tropopause) to the stratiform cloud water budget. The convective condensate thus injected into the stratiform anvil is treated as cloud water and evolves in time, precipitating only partially in a single time step but more efficiently as the mass of the anvil increases. This allows the anvils to persist for hours even if convection has ceased, and it permits us to utilize an interactive calculation of the anvil optical thickness, which has a dramatic effect on cloud feedback. Specifically, since the anvils at any level thicken as the climate warms, they reduce climate sensitivity by off-setting the model II tendency for deeper convection to produce thinner cirrus (DelGenio 1991).

The GCM representation of anvil clouds is compared with in situ aircraft data acquired over Kwajalein in the tropical west Pacific (Heymsfield and Donner 1990) in Fig. 18.3. Despite its simplicity, the scheme produces a realistic temperature dependence of tropical ice water content. In part, this may be the result of radiative heating within the anvil that drives a grid-scale version of a mesoscale updraft in the upper troposphere. As a result, the stratiform fraction of tropical precipitation increases from less than 5% in model II to a more realistic 15% - 20% in the new version of the GCM. It is therefore not obvious that a separate mesoscale parameterization is required in climate GCMs.

We note that all the parameterization changes described in this paper have almost no effect on the combined contributions of water vapor and lapse rate feedbacks to climate sensitivity (DelGenio at al 1991). Even more remarkable is the fact that *all* GCMs without exception produce similar water vapor-lapse rate feedbacks, regardless of whether they use drying mass flux schemes or moistening Kuo or convective adjustment schemes, and regardless of whether they have 2 or 20 vertical levels (Cess et al. 1990). This surprising result occurs because changing large-scale dynamical transports of heat and moisture always offset changes in cumulus heating and drying to produce almost constant relative humidity on climatic time scales (though not on shorter synoptic time scales). We therefore recommend that the emphasis in future cumulus parameterization research for climate models be directed toward quantifying the effects of moist convection on cloud feedback, which is much more sensitive than water vapor feedback to small errors in relative humidity. We also conclude that while one-dimensional models continue to be useful for physical process studies, three-dimensional models that incorporate the effects of large-scale dynamics explicitly will ultimately be the only reliable tool for inference of climate feedbacks.

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Fig. 18.1. Quasi-equilibrium behavior produced by a neutral buoyancy cumulus mass flux closure in the GISS GCM (Yao and DelGenio 1989)

Fig. 18.2. Zonal mean distribution of the change in January temperature (upper) and relative humidity (lower) caused by the inclusion of a recent version of a convective downdraft parameterization in the GISS GCM.

Fig. 18.3. Tropical ice water content versus temperature produced by the GISS cloud water budget parameterization (filled circles) compared with observations (open circles) from Heymsfield and Donner (1990).